

# Practical Troubleshooting of Electrical Equipment and Control Circuits

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# Preface

There is a large gap between the theory of electron flow, magnetic fields and that of troubleshooting electrical equipment and control circuits in the plant. In this book, we try to avoid or at least minimize discussions on the theory and instead focus on showing you how to troubleshoot electrical equipment and control circuits. The book helps to increase your knowledge and skills in improving equipment productivity whilst reducing maintenance costs. Reading this book will help you identify, prevent and fix common electrical equipment and control circuits. The focus is 'outside the box'. The emphasis is on practical issues that go beyond typical electrical theory and focus on providing those that attend with the necessary toolbox of skills in solving electrical problems, ranging from control circuits to motors and variable speed drives.

This book focuses on the main issues of troubleshooting electrical equipment and control circuits of today to enable you to walk onto your plant or facility to troubleshoot and fix problems as quickly as possible. This is not an advanced book but one aimed at the fundamentals of troubleshooting systems. The book is very practical in its approach to troubleshooting and the examples you will be shown are applicable to any facility.

We would hope that you will gain the following knowledge from this book:

- Diagnose electrical problems 'right-first-time'
- Minimize the expensive trial and error troubleshooting approach
- Reduce unexpected downtime on electrical motors and other equipment
- Improve plant safety
- Learn specific techniques to troubleshoot equipment and control circuits
- Analyze equipment problems
- Determine causes of equipment failure
- Troubleshoot electrical equipment and control circuits.

Typical people who will find this book useful include:

- Plant Electricians
- Mechanical Engineers
- Production Operators and Supervisors
- Utilities Maintenance Personnel
- Plant Engineers.

## Pre-requisites

A basic understanding of electrical theory and problems you have encountered in the past would be helpful but a basic review is undertaken at the beginning of the book.

# Basic principles

## Objectives

- To refresh basic electrical concepts
- To define basic concepts of transformer
- To refresh single-phase power concepts
- To refresh three-phase power concepts.

## 1.1 Introduction

A significant proportion of industrial electricity is about single-phase and three-phase transformers, AC and DC machines. In this context, we will study the electrical circuits and their construction, design, testing, operation, and maintenance.

For troubleshooting electrical equipment and control circuits, it is important to understand the basic principles on which the electrical equipment works. The following sections will outline the basic electrical concepts.

### 1.1.1 Basic electrical concepts

In each plant, the mechanical movement of different equipments is caused by an electric prime mover (motor). Electrical power is derived from either utilities or internal generators and is distributed through transformers to deliver usable voltage levels.

Electricity is found in two common forms:

- AC (alternating current)
- DC (direct current).

Electrical equipments can run on either of the AC/DC forms of electrical energies. The selection of energy source for equipment depends on its application requirements. Each energy source has its own merits and demerits.

Industrial AC voltage levels are roughly defined as LV (low voltage) and HV (high voltage) with frequency of 50–60 Hz.

An electrical circuit has the following three basic components irrespective of its electrical energy form:

- Voltage (volts)
- Ampere (amps)
- Resistance (ohms).



## 2 Practical Troubleshooting of Electrical Equipment and Control Circuits

Voltage is defined as the electrical potential difference that causes electrons to flow. Current is defined as the flow of electrons and is measured in amperes.

Resistance is defined as the opposition to the flow of electrons and is measured in ohms.

All three are bound together with Ohm's law, which gives the following relation between the three:

$$V = I \times R$$

Where

$V$  = Voltage

$I$  = Current

$R$  = Resistance.

### (a) Power

In DC circuits, power (watts) is simply a product of voltage and current.

$$P = V \times I$$

For AC circuits, the formula holds true for purely resistive circuits; however, for the following types of AC circuits, power is not just a product of voltage and current.

Apparent power is the product of voltage and ampere, i.e., VA or kVA is known as apparent power. Apparent power is total power supplied to a circuit inclusive of the true and reactive power.

Real power or true power is the power that can be converted into work and is measured in watts.

*Reactive power* If the circuit is of an inductive or capacitive type, then the reactive component consumes power and cannot be converted into work. This is known as reactive power and is denoted by the unit VAR.

### (b) Relationship between powers

$$\text{Apparent power (VA)} = V \times A$$

$$\text{True power (Watts)} = \text{VA} \times \cos \phi$$

$$\text{Reactive power (VAR)} = \text{VA} \times \sin \phi$$

### (c) Power factor

Power factor is defined as the ratio of real power to apparent power. The maximum value it can carry is either 1 or 100(%), which would be obtained in a purely resistive circuit.

$$\text{Power factor} = \frac{\text{True power}}{\text{Apparent power}} \\ \frac{\text{Watts}}{\text{kVA}}$$

### (d) Percentage voltage regulation

$$\% \text{ Regulation} = 100 \frac{(\text{No load voltage} - \text{Full load voltage})}{\text{Full load voltage}}$$

**(e) Electrical energy**

This is calculated as the amount of electrical energy used in an hour and is expressed as follows:

$$\text{Kilowatthour} = \text{kW} \times \text{h}$$

Where

kW = kilowatt

h = hour.

**(f) Types of circuits**

There are only two types of electrical circuits – series and parallel.

A series circuit is defined as a circuit in which the elements in a series carry the same current, while voltage drop across each may be different.

A parallel circuit is defined as a circuit in which the elements in parallel have the same voltage, but the currents may be different.

**1.1.2 Transformer**

A transformer is a device that transforms voltage from one level to another. They are widely used in power systems. With the help of transformers, it is possible to transmit power at an economical transmission voltage and to utilize power at an economic effective voltage.

**Basic principle**

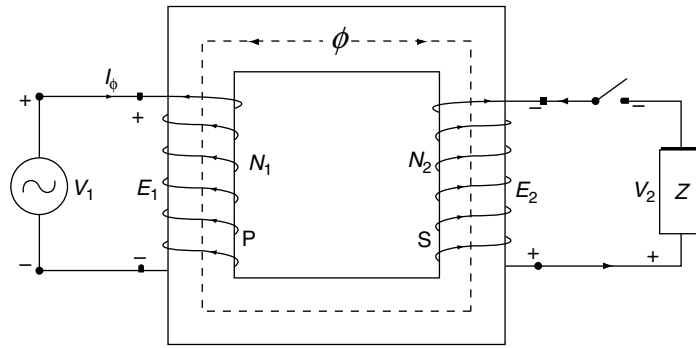
Transformer working is based on mutual *emf* induction between two coils, which are magnetically coupled.

When an AC voltage is applied to one of the windings (called as the primary), it produces alternating magnetic flux in the core made of magnetic material (usually some form of steel). The flux is produced by a small magnetizing current which flows through the winding. The alternating magnetic flux induces an electromotive force (EMF) in the secondary winding magnetically linked with the same core and appears as a voltage across the terminals of this winding. Cold rolled grain oriented (CRGO) steel is used as the core material to provide a low reluctance, low loss flux path. The steel is in the form of varnished laminations to reduce eddy current flow and losses on account of this.

Typically, the coil connected to the source is known as the primary coil and the coil applied to the load is the secondary coil.

A schematic diagram of a single-phase transformer is shown in the Figure 1.1.

A single-phase transformer consists mainly of a magnetic core on which two windings, primary and secondary, are wound. The primary winding is supplied with an AC source of supply voltage  $V_1$ . The current  $I_1$  flowing in the primary winding produces flux, which varies with time. This flux links with both the windings and produces induced emfs. The emf produced in the primary winding is equal and opposite of the applied voltage (neglecting losses). The emf is also induced in the secondary winding due to this mutual flux. The magnitude of the induced emf depends on the ratio of the number of turns in the primary and the secondary windings of the transformer.



**Figure 1.1**  
Schematic diagram of a single-phase transformer

### Potential-induced

There is a very simple and straight relationship between the potential across the primary coil and the potential induced in the secondary coil.

The ratio of the primary potential to the secondary potential is the ratio of the number of turns in each and is represented as follows:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2}$$

The concepts of step-up and step-down transformers function on similar relation.

A step-up transformer increases the output voltage by taking  $N_2 > N_1$  and a step-down transformer decreases the output voltage by taking  $N_2 < N_1$ .

### Current-induced

When the transformer is loaded, then the current is inversely proportional to the voltages and is represented as follows:

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2}$$

EMF equation of a transformer:

rms value of the induced emf in the primary winding is:

$$E_1 = 4.44 \times f \times N_1 \times \phi_m$$

rms value of the induced emf in the secondary winding is:

$$E_2 = 4.44 \times f \times N_2 \times \phi_m$$

Where

$N_1$  = Number of turns in primary

$N_2$  = Number of turns in secondary

$\phi_m$  = Maximum flux in core and

$f$  = Frequency of AC input in Hz.

### 1.1.3 Ideal transformer

The following assumptions are made in the case of an ideal transformer:

- No loss or gain of energy takes place.
- Winding has no ohm resistances.
- The flux produced is confined to the core of the transformer, which links fully both the windings, i.e., there is no flux leakage.
- Hence, there are no  $I^2R$  losses and core losses.
- The permeability of the core is high so that the magnetizing current required to produce the flux and to establish it in the core is negligible.
- Eddy current and hysteresis losses are negligible.

### 1.1.4 Types of transformers

#### 1. As per the type of construction

- (a) *Core type*: Windings surround a considerable part of the core.
- (b) *Shell type*: Core surrounds a considerable portion of the windings.

#### 2. As per cooling type

- (a) *Oil-filled self-cooled*: Small- and medium-sized distribution transformers.
- (b) *Oil-filled water-cooled*: High-voltage transmission line outdoor transformers.
- (c) *Air Cooled type*: Used for low ratings and can be either of natural air circulation (AN) or forced circulation (AF) type.

#### 3. As per application

- (a) *Power transformer*: These are large transformers used to change voltage levels and current levels as per requirement. Power transformers are usually used in either a distribution or a transmission line.
- (b) *Potential transformer (PT)*: These are precision voltage step-down transformers used along with low-range voltmeters to measure high voltages.
- (c) *Current transformer (CT)*: These transformers are used for the measurement of current where the current-carrying conductor is treated as a primary transformer. This transformer isolates the instrument from high-voltage line, as well as steps down the current in a known ratio.
- (d) *Isolation transformer*: These are used to isolate two different circuits without changing the voltage level or current level.

A few important points about transformers:

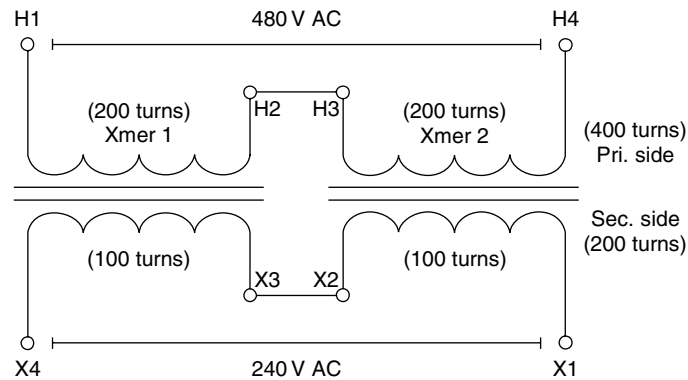
- Used to transfer energy from one AC circuit to another
- Frequency remains the same in both the circuits
- No ideal transformer exists
- Also used in metering applications (current transformer, i.e., CT, potential transformers, i.e., PT)
- Used for isolation of two different circuits (isolation transformers)
- Transformer power is expressed in VA (volt amperes)
- Transformer polarity is indicated by using dots. If primary and secondary windings have dots at the top and bottom positions or vice versa in diagram, then it means that the phases are in inverse relationship.

### 1.1.5 Connections of single-phase transformer

Depending on the application's requirement, two or more transformers have to be connected in a series or parallel circuits. Such connections can be undertaken as depicted in the following diagram examples:

#### (a) Series connection of two single-phase transformers

As shown in Figure 1.2, two transformers can be connected in a series connection. If both are connected as in Figure 1.2 then voltage twice that of voltage rating of the individual transformer can be applied. Their current rating must be equal and high enough to carry load current. Precaution should be taken to connect transformers windings, keeping in mind the polarity. In the above example, primary total turns to secondary total turns are in the 2:1 ratio, leading to half voltage.

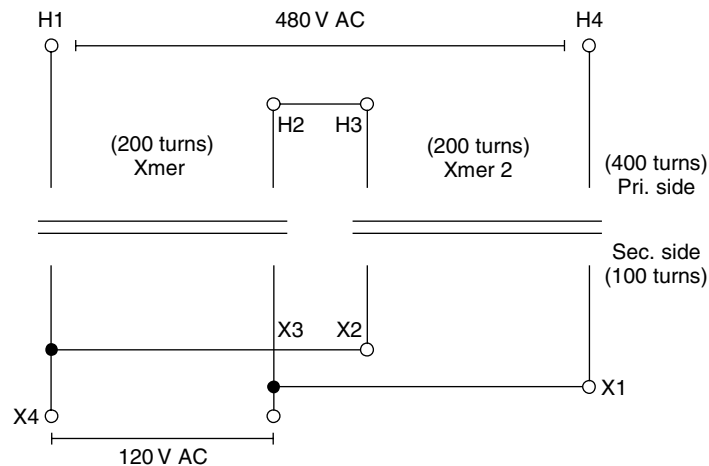


**Figure 1.2**

*Series connection of two single-phase transformers*

#### (b) Parallel connection of two single-phase transformers

As shown in Figure 1.3, two transformers are connected in series on the primary side while the secondary sides are connected in parallel.



**Figure 1.3**

*Parallel connection of two single-phase Transformers*

On the primary side, the number of turns is added while on the secondary side they remain as it is due to their parallel condition.

LVDT (linear voltage differential transformer) is the best practical example of the basic transformer and its series connection. Use of transformers with such connections can pose problems of safety and load sharing and are hardly used in practical power circuits. It is possible to deploy these connections while designing control transformers if such use will have any specific advantage. Parallel operation of two separate transformers is possible under specific conditions to meet an increased load requirement but the risks involved must be properly evaluated.

### 1.1.6 Three-phase transformers

Large-scale generation of electric power is generally three-phasic with voltages in 11 or 32 kV. Such high three-phasic voltage transmission and distribution requires use of the three-phase step-up and step-down transformers.

Previously, it was common practice to use three single-phase transformers in place of a single three-phase transformer. However, the consequent evolution of the three-phase transformer proved space saving and economical as well.

Still, construction-wise a three-phase transformer is a combination of three single-phase transformers with three primary and three secondary windings mounted on a core having three legs.

Commonly used three-phases are:

- Three-phase three-wire (delta)
- Three-phase four-wire (star).

#### 1. *Delta connection*

It consists of three-phase windings (Figure 1.4) connected end-to-end and are  $120^\circ$  apart from each other electrically. Generally, the delta three-wire system is used for an unbalanced load system. The three-phase voltages remain constant regardless of load imbalance.

$$V_L = V_{ph}$$

Where

$V_L$  = line voltage

$V_{ph}$  = phase voltage.

Relationship between line and phase currents:

$$I_L = \sqrt{3} I_{ph}$$

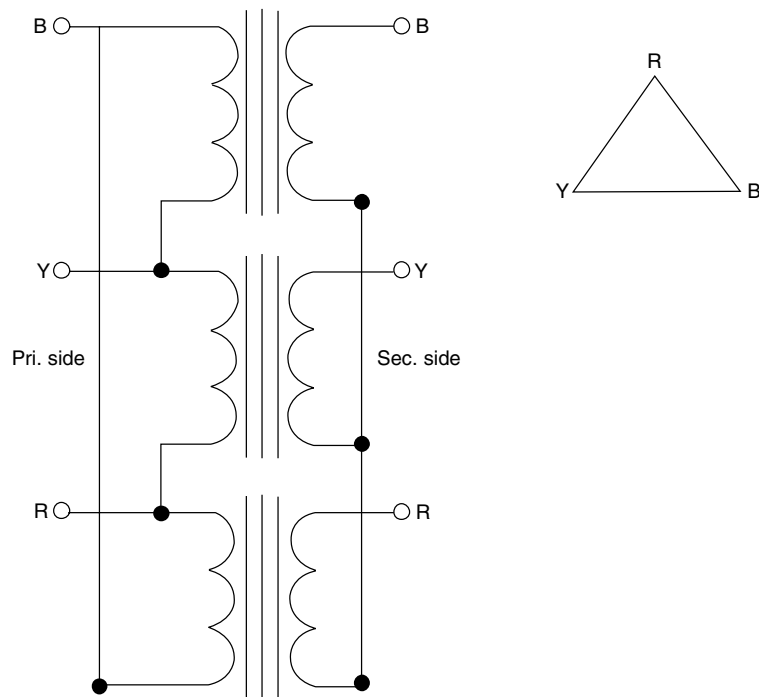
Where

$I_L$  = line current

$I_{ph}$  = phase current.

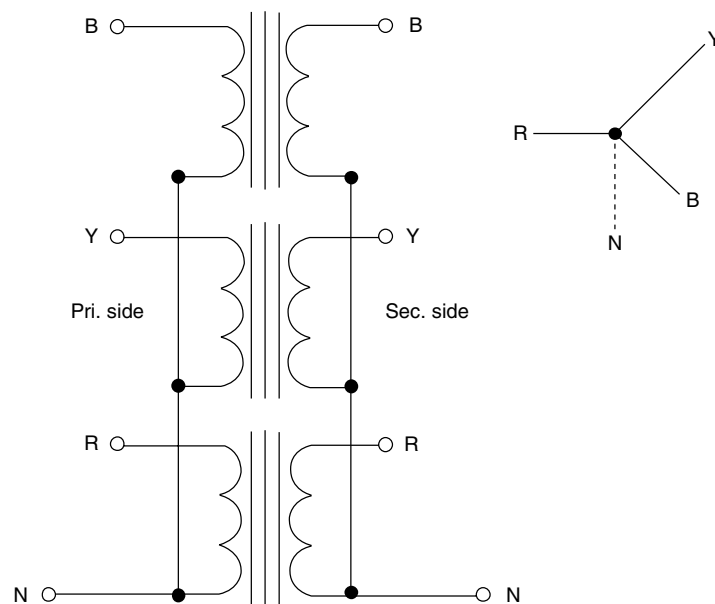
#### 2. *Three-phase four-wire star connections*

The star type of construction (Figure 1.5) allows a minimum number of turns per phase (since phase voltage is  $1/\sqrt{3}$  of line voltage) but the cross section of the conductor will have to be increased as the current is higher compared to a delta winding by a factor of  $\sqrt{3}$ . Each winding at one end is connected to a common end, like a neutral point – therefore, as a whole there are four wires.

**Figure 1.4**

*Three-phase transformer delta connection on primary side*

A three-wire source as obtained from a delta winding may cause problems when feeding to a star connected unbalanced load. Because of the unbalance, the load neutral will shift and cause change of voltage in the individual phases of the load. It is better to use a star-connected four-wire source in such cases. Three-wire sources are best suited for balanced loads such as motors.

**Figure 1.5**

*Three-phase four-wire transformer star connection*

Relationship between line and phase voltages:

$$V_L = \sqrt{3} V_{ph}$$

Where

$V_L$  = line voltage

$V_{ph}$  = phase voltage.

Relationship between line and phase currents:

$$I_L = I_{ph}$$

Where

$I_L$  = line current

$I_{ph}$  = phase current.

Output power of a transformer in kW:

$$P = \sqrt{3} \times V_L \times I_L \times \cos \phi \text{ [kW]}$$

Where

$V_L$  = line voltage

$I_L$  = line current

$\cos \phi$  = power factor.

### 3. Possible combinations of star and delta

The primary and secondary windings of three single-phase transformers or a three-phase transformer can be connected in the following ways:

- Primary in delta – secondary in delta
- Primary in delta – secondary in star
- Primary in star – secondary in star
- Primary in star – secondary in delta.

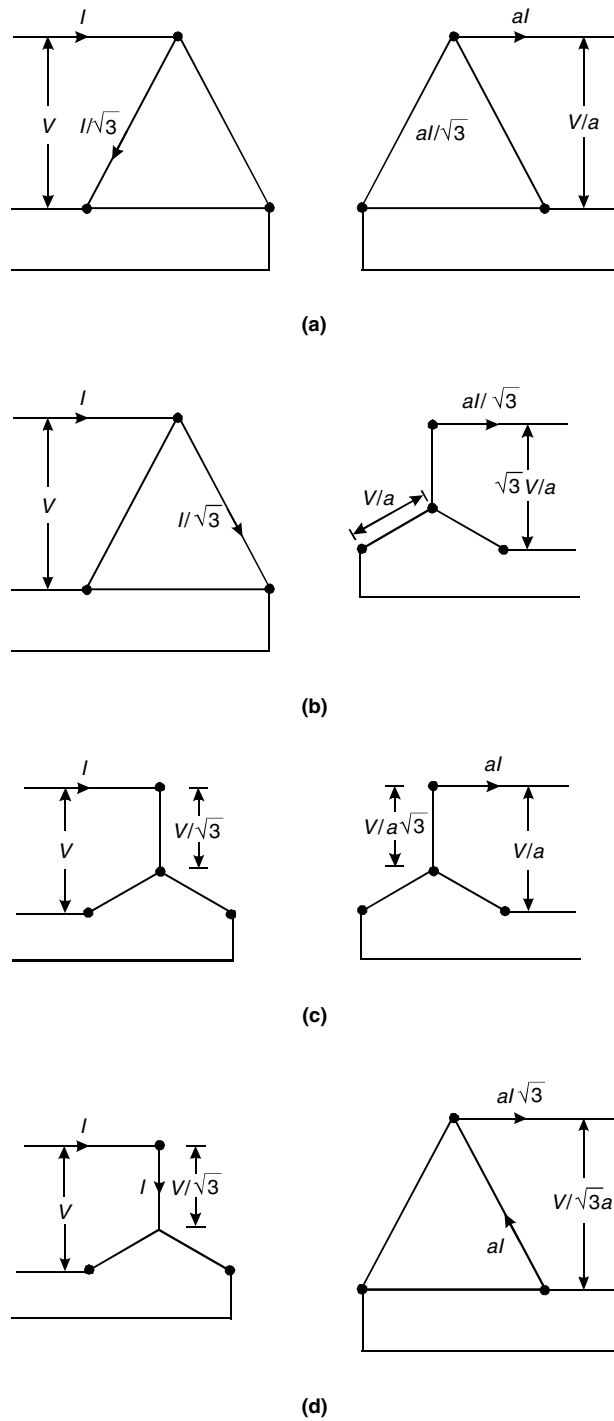
Figure 1.6 shows the various types of connections of three-phase transformers. On the primary side,  $V$  is the line voltage and  $I$  the line current. The secondary sideline voltages and currents are determined by considering the ratio of the number of turns per phase ( $a = N_1/N_2$ ) and the type of connection. Table 1.1 gives a quick view of primary-line voltages and line currents and secondary-phase voltages and currents. The power delivered by the transformer in an ideal condition irrespective of the type of connection =  $1.732 V_L I_L$  assuming  $\cos \phi = 1$ .

## 1.1.7 Testing transformers

The following tests are carried out on transformers:

- Measurement of winding resistance
- Measurement of Voltage ratio
- Test phasor voltage relationship
- Measurement of impedance voltage, short-circuit impedance and load loss
- Measurement of no load loss and no load current
- Measurement of insulation resistance
- Dielectric test
- Temperature rise.





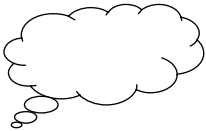
**Figure 1.6**

*Types of connections for three-phase transformers: (a) Delta–delta connection; (b) Delta–star connection; (c) Star–star connection; (d) Star–delta connection*

Connection	Line Voltage	Line Current	Phase Voltage	Phase Current
(a) Delta–delta				
Primary delta	$V$	$I$	$V$	$I/1.732$
Secondary delta	$V/a$	$Ia$	$V/a$	$Ia/1.732$
(b) Delta–star				
Primary delta	$V$	$I$	$V$	$I/1.732$
Secondary star	$1.732V/a$	$Ia/1.732$	$V/a$	$Ia/1.732$
(c) Star–star				
Primary star	$V$	$I$	$V/1.732$	$I$
Secondary star	$V/a$	$Ia$	$V/1.732 a$	$Ia$
(d) Star–delta				
Primary star	$V$	$I$	$V/1.732$	$I$
Secondary delta	$V/1.732a$	$1.732 Ia$	$V/1.732 a$	$Ia$

**Table 1.1**

*Voltage and current transformation for different three-phase transformer connections*

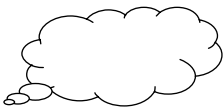


### ***Why is transformer rating defined in kVA?***

A transformer, unlike a motor, has no mechanical output (expressed in kW). The current flowing through it can vary in power factor, from zero PF lead (pure capacitive load) to zero PF lag (pure inductive load) and is decided by the load connected to the secondary. The conductor of the winding is rated for a particular current beyond which it will exceed the temperature for which its insulation is rated irrespective of the load power factor.

Similarly, the voltage that can be applied to a transformer primary winding has a limit. Exceeding this rated value will cause magnetic saturation of the core leading to distorted output with higher iron losses.

It is therefore usual to express the rating of the transformer as a product of the rated voltage and the rated current (VA or kVA). This however does not mean that you can apply a lower voltage and pass a higher current through the transformer. The VA value is bounded individually by the rated voltage and rated current.



### ***Why is power transmitted at higher voltages?***

When a particular amount of power has to be transmitted over a certain distance the following aspects need to be considered to decide the best voltage.

A lower voltage the need higher size conductors to withstand the high current involved. There is a physical limitation to the size of conductor. Also, the percentage voltage drop may become excessive. A higher voltage will make the conductor size manageable and reduce the voltage drop (% value) but the cost of the line becomes high due to larger clearances needed.

The best voltage will be one in which the total operational cost which the sum of the annualized capital cost (of the line) and the running cost due to power loss in the line is the lowest. In practice, it is found that transmitting bulk power over long distances is economical if done in the HV range. The actual voltage will vary based on the distance

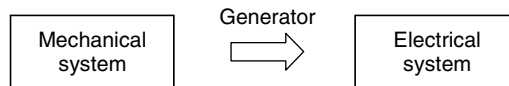
and quantum of power. Distribution circuits where typically the amount of power and distance involved are both lower, the best voltage is in the MV range (11, 22 or 33 kV). For the same reason, low voltage circuits are found only in local sub-distribution circuits.

## 1.2 Basic principles of electrical machines

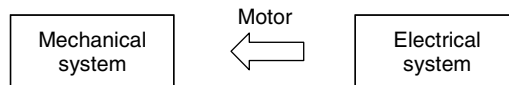
### 1.2.1 Electromechanical energy conversion

The electromechanical energy conversion device is a link between electrical and mechanical systems.

When the mechanical system delivers energy through the device to the electrical system, the device is called a generator.



When an electrical system delivers energy through the device to the mechanical system, the device is called a motor.



The process is reversible; however, the part of energy converted to heat is lost and is irreversible. An electric machine can be made to work either as a generator or as a motor. The electromechanical conversion depends on the interrelation between:

- Electric and magnetic fields
- Mechanical forces and motion.

In rotating machines, power is generated by the relative motion of the coils.

In the case of a generator, the winding is rotated mechanically in the magnetic field. This causes the flux linkages with the windings to change causing induced voltages.

In the case of a motor, the current-carrying conductor is allowed inside a magnetic field. Mechanical force is exerted on a current-carrying conductor in a magnetic field and hence a resultant torque is produced to act on the rotor.

In both a generator as well as a motor, the current-carrying conductor is in the magnetic field. The conductors and flux travel with respect to each other at a definite speed. In rotating machines, both voltage and torque are produced. Only the direction of power flow determines whether the machine is working as a generator or a motor. For a generator,  $e$  and  $i$  are in the same direction.

$$T_m = T_e + T_f$$

Where

$T_m$  = mechanical torque

$T_e$  = electrical torque

$T_f$  = torque lost due to friction.

For a motor,  $e$  and  $i$  are in opposite direction.

$$T_m = T_e + T_f$$

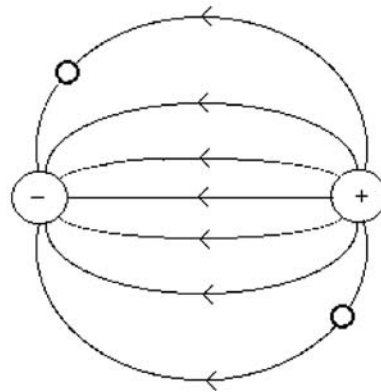
In a generator, the power is supplied by the prime mover. Electrical power is produced by the action of the generator and the resultant power produced due to friction is lost. Whereas in the case of a motor, the power is supplied by the electrical power supply inputs, and there is a slight loss of the resultant mechanical power produced due to friction.

## 1.2.2 Basic principles of electromagnetism

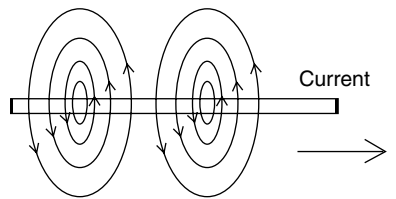
### Magnetic and electric fields

As you are aware, each electric charge has its own electric field; i.e., lines of force. Electric field lines point away from the positive charges and towards negative charges (Figure 1.7). Each charge exerts force on the other charge, which is always tangential to the lines of force created by the other charge.

Similarly, the magnetic field lines 'flow' away from the N-pole and towards the S-pole (Figure 1.8). A current moving the electric charges creates a magnetic field. Every orbiting electron forms a current loop that creates its own magnetic field. Magnetic field lines always form circles around the current creating them.



**Figure 1.7**  
*Electric force line of a charge*



**Figure 1.8**  
*Magnetic field lines around a current-carrying conductor*

### Magnetic field produced by a current-carrying conductor

If a conductor carries a current, it produces a magnetic field surrounding it. The direction of the current and the direction of the field so produced have a definite relation that is given by the following rules:

**The right hand rule** Hold the conductor in the right hand with the fingers closed around the conductor and the thumb pointing towards in the direction of the current. The fingers will point towards the direction of the magnetic lines of the flux produced around the conductor.

**Flux produced by a current-carrying coil** Flux can be produced by causing the current to flow through a coil instead of a conductor. Introduction of magnetic material in the core on which the coil is wound increases flux. The direction of the magnetic flux in the coil is given by the right-hand rule.

In the case of a motor, the direction of the emf induced is such as to oppose the flow of current. Whereas, in a generator the emf induced is in such a direction as to establish a current.

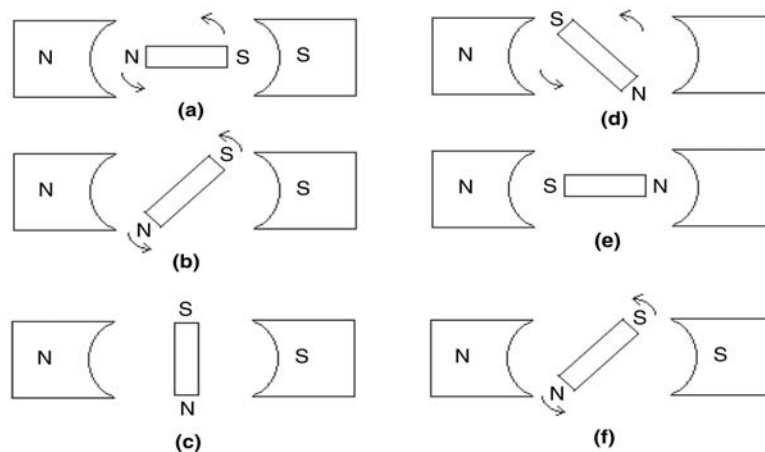
**Fleming's left hand rule** This defines the relationship between the direction of the current, the direction of field, and the direction of the motion. If the forefinger of the left hand points in the direction of the field, the middle finger points in the direction of the current, and the thumb points in the direction of the motion.

### 1.2.3 The basic principle of motor

The basic working of a motor is based on the fact that when 'a current carrying conductor is placed in a magnetic field, it experiences a force'.

If you take a simple DC motor, it has a current-carrying coil supported in between two permanent magnets (opposite pole facing) so that the coil can rotate freely inside. When the coil ends are connected to a DC source then the current will flow through it and it behaves like a bar magnet, as shown in Figure 1.9. As the current starts flowing, the magnetic flux lines of the coil will interact with the flux lines of the permanent magnet. This will cause a movement of the coil (Figures 1.9(a), (b), (c), (d)) due to the force of attraction and repulsion between two fields. The coil will rotate until it achieves the  $180^\circ$  position, because now the opposite poles will be in front of each other (Figure 1.9(e)) and the force of attraction or repulsion will not exist.

**The role of the commutator:** The commutator brushes just reverse the polarity of DC supply connected to the coil. This will cause a change in the direction of the current of the magnetic field and start rotating the coil by another  $180^\circ$  (Figure 1.9(f)).



**Figure 1.9**  
A motor action

The brushes will move on like this to achieve continuous coil rotation of the motor.

Similarly, the AC motor also functions on the above principle; except here, the commutator contacts remain stationary, because AC current direction continually changes during each half-cycle (every  $180^\circ$ ).

## 1.2.4 Basic principle of generator

We have discussed the basic working of a motor and through the diagrams we have seen a generator action as well.

In principle, an AC generator's construction is similar to the construction of the motor. Instead of putting current in, current is taken out from the coil in an alternator.

A mechanical prime mover rotates the coil in between the poles of a permanent magnet and an AC potential is induced in the coil. To further define: if an AC current will make a coil turn, then turning the coil will create an AC current.

As per Faraday's law, when a wire is moved in to cut across magnetic field lines, a force is exerted on the charge (electrons) in the wire by trying to move them along the wire. This is how current will start flowing if a complete circuit is provided to it. The magnetic field is provided not by magnets, but by field coils.

The coil in which the voltage is induced is called armature winding, while the coil that provides the magnetic field is called field winding.

In high-voltage generators, it is not good practice to have armatures rotating because current-collecting brushes of high ratings are required. Rather, the armature is kept stationary and the field is kept rotating.

Alternators of low capacity use a permanent magnet as a field, while in high-capacity alternators field winding supply is derived from the exciter assembly. An exciter assembly is a small alternator connected on the same shaft.

## 1.2.5 Idealized machines

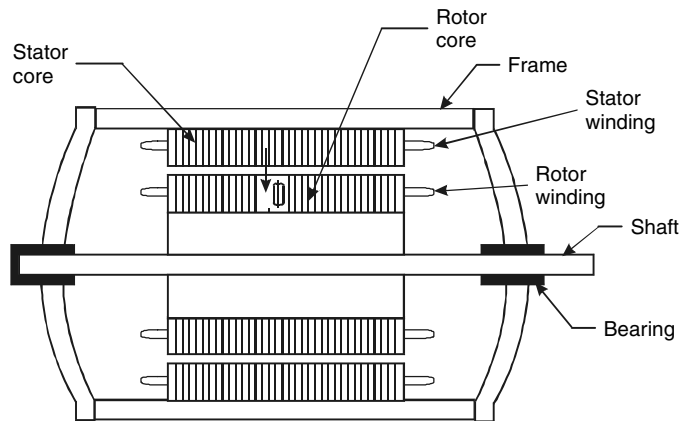
There is a stationary member called a stator and a rotating member called a rotor. The rotating member is mounted on bearings fixed to the stationary member. The stator and the rotor have cylindrical iron cores, separated by an air gap. Windings are wound on the stator and the rotor core. A common magnetic flux passes across the air gap from one core to another forming a combined magnetic circuit. Two cylindrical iron surfaces with an air gap between them move relative to each other. The cylindrical surface may be divided by an even number of salient poles with spaces in between, or it may be continuous with slot openings uniformly spaced around the circle. This structure may be for either of the stator or the rotor.

The common features of an ideal electrical machine are shown in the Figure 1.10. For windings, conductors run parallel to the axis of the cylinders near the surface. The conductors are connected into coils by the end connections outside the core and the coils are connected to form the windings of the machine.

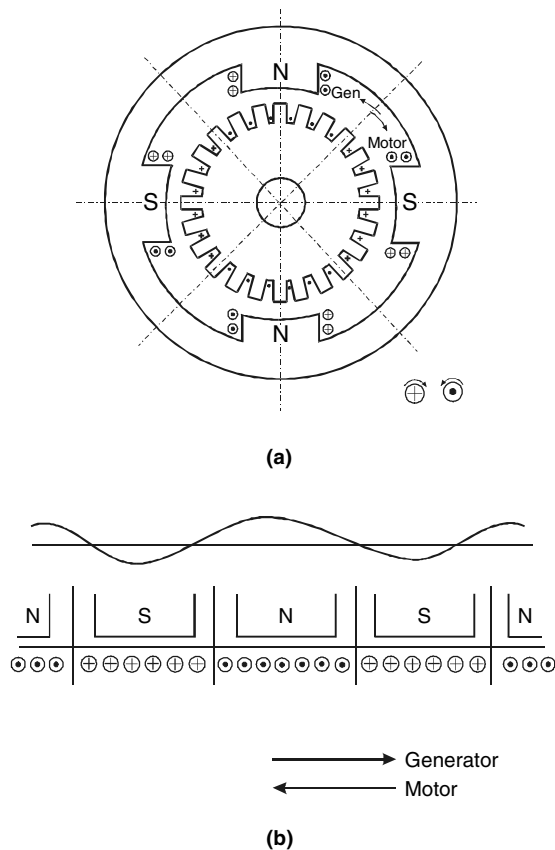
The operation of the machine depends on the distribution of the currents around the core surfaces and the voltages applied to the windings.

In various types of electrical machines, the arrangement differs in the distribution of the conductors, windings, and in core constructions, depending on whether it is a continuous or a salient pole type. The magnetic flux permeates the iron cores in a complex manner. However, as the iron has a high permeability, the accurate working of a machine can be determined by considering the flux distribution in the air gap. The conductors are actually located in slots formed in the laminations of the core.

A typical cross section and the corresponding development diagram of an electrical machine with four poles, perpendicular to the axis of the cores is shown in Figure 1.11. As shown in the diagram, the distribution of flux and current repeats itself at every pair of poles. On the poles, the windings are so wound that the current flows in the opposite direction and produces a field corresponding to the north and south polarities. Maximum flux is along the center of the pole and reduces to zero between the interpole gaps.



**Figure 1.10**  
*Common features of an ideal electric machine*



**Figure 1.11**  
*Typical cross section and development of an electrical machine*

### 1.2.6 Basic principles of electrical machines

In an electrical machine, the currents in all the windings combine to produce the resultant flux. The field system produces flux. Voltages are induced in the windings such as those of an armature. When the armature carries current, the interaction between the flux and the current produces torque.

## Types of electrical machine windings

### (a) *Coil winding*

The winding consists of coils wound on all the poles of the machine and connected together to form a suitable series or parallel circuit. The direction of the current in the alternate pole will be opposite so that when one pole is the North Pole, the other adjacent pole will be a South Pole. This produces the flux in the proper direction, completing the magnetic circuit from the North Pole to the South Pole through the iron cores of both the stator and the rotor.

The coil may be wound on the stator or on the rotor, forming the salient or non-salient poles of the machine. The DC supply is given to these windings and they produce a field proportional to the magnitude of the current through the windings. If the poles are on the stator, a stationary field is produced in the air gap.

### (b) *Commutator winding*

The commutator winding is on the rotor. The armature has open slots and the conductors are located in these slots and connected to the commutator segments in a continuous sequence.

### (c) *Polyphase winding*

Polyphase winding is a distributed winding. Individual conductors are distributed in slots in a suitable way and connected into a number of separate circuits, one for each phase. The group of conductors forming the phase bands is distributed in a regular sequence over the successive pole pitches so that there is balanced winding that produces an equal voltage per phase. This type of winding is mainly used for the stator. When supplied with three-phase currents it produces a rotating field in the air gap. This is of a constant magnitude but rotating at a constant synchronous speed.

## 1.2.7 Types of electrical machines

Depending on the type of combinations of windings used on the stator and the rotor, electrical machines are classified in different types as follows:

### 1. *DC machines*

The DC machines have an edge over AC machines when it comes to the speed control of a motor. It is easier and cheaper.

#### (a) *Shunt motor*

This machine has field winding mounted in yoke and the armature winding is mounted on rotor. The shunt motor is used where speed regulation is important.

*Self excited* Field winding is connected in parallel (shunt) with the armature winding on the same supply. Changing the field current can vary the speed. Torque is proportional to armature current.

This machine can also act as a generator. To limit the high starting current of the motor drive release the voltage in the ramp. For this motor, a variable resistor is connected in series with the field circuit to change the flux value and the speed by a small amount.

*Separately excited* Field winding is connected in parallel (shunt) with the armature winding with separate excitation.



Torque is proportional to armature current. In a separately excited shunt motor, speed can be varied up to a certain limit by changing armature voltage. After that using field weakening (reducing field current), it is possible to increase the speed of motor above base speed. Other features remain same as that of the self-excited one.

### (b) *Series motor*

As the name suggests in this type of motors, field winding is connected in series with the armature winding. Naturally, heavy current will pass through it; hence field winding of a thicker gage is used. A series motor is used where speed regulation is not important.

The main advantage of this motor is that a high torque can be obtained, which makes it useful for applications such as diesel locomotives, cranes, etc.

The relationship between Torque and current is as follows:

$$T \propto Ia^2$$

It is important to start this motor in a loaded condition else it could lead to damage of the motor and its surroundings.

### (c) *Compound motor*

If we combine both series and shunt motors then we will have a compound motor. This combines the good features of both types such as high torque characteristics of a series motor and the speed regulation of a shunt motor.

## 2. *AC machines*

### (a) *Squirrel-cage induction motor*

AC machines are simple and sturdy. The most common machine of this type is the Squirrel cage induction motor (the name was derived from its construction type). The basic working of this was dealt with in the previous sections. The following relation gives the speed of this motor:

$$N \text{ (rpm)} = \frac{120f}{p}$$

Where

$f$  = frequency

$p$  = number of poles.

For example, if the motor has two poles, then at 50 Hz frequency the motor rpm will be 3000 (rpm).

However, you will not find 3000 or 1500 rpm on the motor nameplate because the motor rpm will not be 3000 rpm at full load. This is because of a slip associated with an induction motor.

The RPM of the motor is controlled by controlling the frequency ( $f$ ) – as frequency increases, motor speed will also increase. High starting current is limited using a star/delta starter or reduced-voltage starters.

### (b) *Wound rotor motor*

This is similar in construction to the squirrel cage and works similarly too, except that slip rings are provided. The main feature of the slip ring motor is that resistors, which are connected in series with the rotor circuit, limit the starting current.